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Analysis of Magnetization Change with Temperature in an Artificial Spin Ice Network by Three Dimensional Finite Element Modeling

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ABSTRACT

A three dimensional finite element model calculation was constructed, which includes different submodels, all as a function of temperature, using an iterative approach, to investigate permalloy artificial spin ice network with square geometry on thermal annealing while applying a voltage pulse. Magnetization is also included into the simulation with an equation defining the change of the magnetization with temperature. The maximum temperature is obtained around the sharp corners due to current crowding, and therefore, minimum magnetization values are observed around the same place, even zero magnetization depending on the applied pulse magnitude and width, because of Curie temperature of permalloy. The aim of this study is to understand the dynamic behavior of the artificial spin ice network according to programming pulse and the importance of the device design to minimize the effect of joule heating.

Keywords: Artificial spin ice, Finite element modelling, Magnetization change,.

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Introduction

Magnetic configurations give scientists variety of the device designs for different purposes, such as, a sensor, oscillator or detector and so on. One of them is magnetic crystal, known as artificial spin ice (ASI) which is a new crystal arrangement to modify magnetic properties [1-5]. With advanced nanotechnology design, scientist can enable the generation of connected ferromagnetic nanowire networks such as magnetic metamaterials [6, 7] . Artificial spin ice is fabricated lithographically 2D ferromagnetic nanoscale islands to create an imitation of the complex magnetic order and collective behavior of magnetic islands [1, 5, 7, 8]. There are many areas of usage of ASI such as to study geometrical frustration and potential applications such as an information storage, signal propagation, and logic devices due to properties like ferromagnetic resonance (FMR) signal in the GHz-regime [9-18], although, there are few study about annealing the arrays to temperature near or above the Curie temperature of the ferromagnetic materials [19, 20]. Therefore, for these wide range studying area, the static and dynamic behaviors of the ASI structures should be studied in a systematic path in high temperature, while using a connected ASI network as a circuit element. For this purpose, the role of the current injection in a nanoscale ASI cell as a magnetic network should be studied to oversee temperature distribution without disturbing magnetic properties of magnetic network.

Heating profile is important for a device working parameters because temperature is a significant factor to effect the magnetic properties of the network. First, 3D finite element simulation was carried out in an ASI cell to understand the complex nature of the ASI network by using COMSOL multiphysics. Simulation is consisted of electrical and thermal effects as a function of temperature, and also magnetization is added as an equation depending on the temperature. All of them are combined with iterative approach with coupled differential equations and also Seeback coefficient was included to account for thermoelectric effect. The simulation results report that the heating profile is mainly due to isotropic/anisotropic heating depending on the geometry and amplitude of the current pulse. The model successfully predicts the temperature distribution and magnetization change during applied current pulse depending on the shape of the network.

A device design needs a clear explanation to understand not only the temperature, but also magnetization change according to applied voltage, especially, for magnetization which is an important parameter to design a magnetic device with spin ice frustration. Therefore, it is important to investigate with 3D finite element model for a network by using a square spin ice geometry

Material and Method

Device Structure

Device geometry is illustrated in Figure 1. Patterned permalloy (NiFe) ASI cell structure is sandwiched between two 50 nm thick WTi metal electrodes. Au layer is also used for contact electrode and to isolate the device from the environment, Al_2O_3 is used. Current pulse is applied from top contact to ASI. The thickness of permalloy is 10 nm.

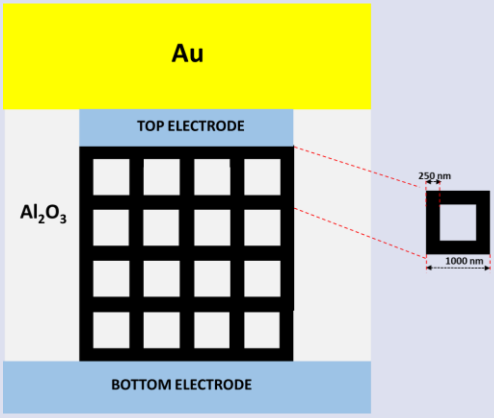

Figure 1. Artificial spin ice (ASI) cell structure and its dimensions.

3D Finite Element Model

It is crucial to know the momentary solution of equations in every point and every time in device during simulation. In the simulation, different equations (like Laplace equation, heat diffusion equation, magnetization change equation) are solved depending on the temperatures of the materials. Therefore, different sub models were constructed to solve the equations for each mesh element. In the electrical model, Laplace equation is solved iteratively (with 0.1ns time range) and to obtain the electrical potential distribution F(x,y,z), thermal submodel is combined to electrical model.

$$\nabla.[\sigma.\nabla F] \qquad (1)$$

Where σ is the electrical conductivity of the materials. At room temperature resistivity ρ is 202.4 μΩ.cm [21]. It has to be note that σ (1/ ρ) electrical conductivity has temperature dependence, therefore, with temperature increase, Permalloy becomes highly conductive due to σ electrical conductivity.

In thermal model, due to electrical potential in device, there are two important parameters to contribute,

$$Q = (JA)^2.R\Delta t. \qquad (2)$$

where A and Δt is the cross-sectional area and the simulation time step, respectively. J and R parameters are electrical current density and the resistance value of the material. Heat diffusion equation answers how the temperature is distributed in materials, therefore, the heat equation is solved iteratively to obtain temperature distribution T(x,y,z) in every point and time in device during simulation.

$$C\,\partial T/\partial t-\nabla.[\kappa\nabla T]=Q+Q_{th} \qquad (3)$$

Where C and κ is the heat capacity and the thermal conductivity, respectively. To account for the contribution of thermoelectric effect, Q_{th}=-TJ∇S is added to simulation. Where S temperature dependence Seebeck coefficient and the equation is following [22].

$$\nabla S=dS/dt.\nabla T \qquad (4)$$

For permalloy, room temperature thermal conductivity κ value is 23 W/(m.K) [23] and Seebeck coefficient S value is 83.1 μV/K [24]. For the magnetization of the Permalloy, I used an equation representing the change of magnetization according to temperature as following,

$$m(T)=m(0)(1-T/T_c)^{\beta} \qquad (5)$$

where β is coefficient from the obtained a 3D Heisenberg model [25] and TC is the Curie temperature of permalloy.

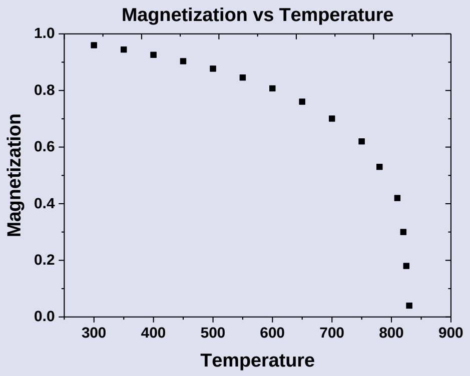

Figure 2. Magnetization vs temperature for permalloy used in simulation [26].

In a device structure, due to joule heating, change in the magnetization should be observed during simulation. The graph of equation of magnetization vs temperature for Permalloy used in simulation is given in Figure 2. The equation from the study, J Fassbender et al 2009 [26] was modified and used in the simulation.

Simulation Results

During an applied voltage pulse 2V with 10 ns width and 2 ns trailing edge, the maximum temperature value is observed as 855.15 K at 9.7 ns and obtained magnetization change according to temperature is given in Figure 3. We can see the counter line for temperature and magnetization. Around the shape corner, counter line numbers are getting more and it is evidence to see maximum temperature and min magnetization value. As you can see here, because of current crowding, maximum temperature minimum magnetization is also obtained around the same corners. However, reaching Curie temperature of Permalloy, magnetization goes to zero because of being paramagnet and in the Figure 3b) blue color corresponds to zero magnetization from the color code for magnetization rate. Thermoelectric effect is small compare to Joule heating due to very short distance.

The graph of temperature and magnetization change at point P with an applied voltage pulse are given in Figure 4. It is clear to see that, after applying 10 ns pulse but due to falling edge, maximum temperature is observed less than

10 ns and minimum magnetization due to the Curie temperature of permalloy was observed. Curie temperature of permalloy is around 833 K [26] and even we can see the results from the observed data

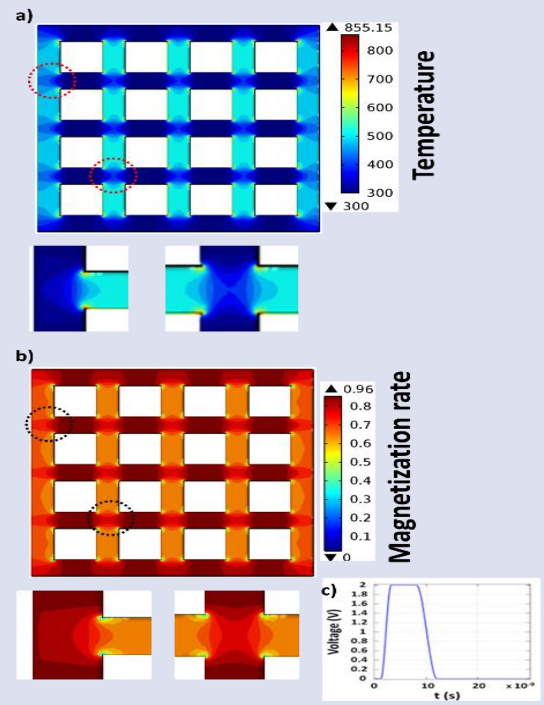

Figure 3. Magnetization vs a) Temperature and b) Magnetization change at 9.7 ns from the center slice and counter line to see the change when 10 ns width 2 V magnitude voltage pulse was applied c). Color codes correspond temperature in a) and magnetization rate in b).temperature for permalloy used in simulation [26].

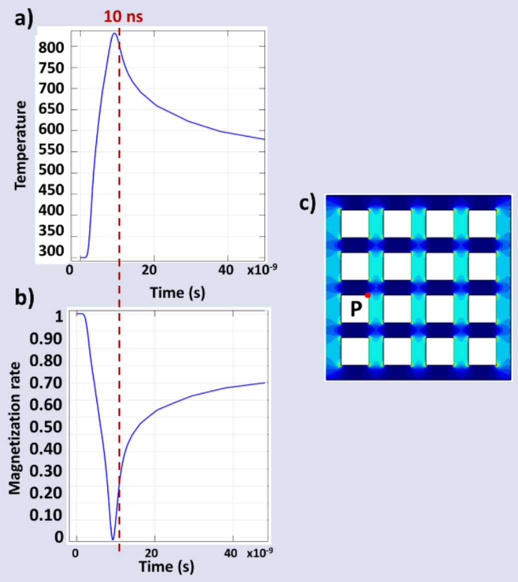

Figure 4. a) Temperature and b) Magnetization versus time at point P in c) for an applied voltage pulse of 2V, with 10 ns width and 2 ns trailing edge. Due to trailing edge, maximum temperature was obtained at 9.7 ns.

After 9.7ns, the magnetization increases with decreasing temperature, namely permalloy again demonstrates ferromagnetic behavior. However, this is very important to know while fabricating a magnetic device, especially estimating programing current to avoid losing magnetic properties of a ferromagnetic material. Therefore, for scientist, device design and material selection is crucial issues to fabricate new magnetic device without losing magnetic properties of the device.

Discussion and Conclusion

In this study, the aim is to understand behavior of a magnetic network by using an electrical device while applying a voltage pulse and device design importance without losing magnetic properties. Due to joule heating, there is a temperature increase in the device and a possibility to lose magnetic properties. Temperature is a crucial factor for a magnetic material, especially around Curie temperature. Therefore, to avoid magnetization loss of device, applied programing pulse and device design to decrease the effect of joule heating are fundamental factor to fabricate a magnetic device to use for different purposes such as, sensor, detector or oscillator.

Conflicts of interest

The authors state that did not have conflict of interests.

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